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Potential impact of climate change on rainfed wheat production in Iran

(Potentieller Einfluss des Klimawandels auf die Weizenproduktion unter Rainfed-Bedingungen im Iran)

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Abstract
Mean monthly weather data values from 1968 – 2000 for 12 major rainfed wheat production areas in north-west and western Iran were used with a climate model, United Kingdom Meteorological Organization (UKMO), to predict the impact of climate change on rainfed wheat production for years 2025 and 2050. The crop simulation model, World Food Study (WOFOST, v 7.1), at CO_2 concentrations of 425 and 500 ppm and rising air temperature of 2.7 – 4.7°C, projected a significant rainfed wheat yield reduction in 2025 and 2050. Average yield reduction was 18 and 24% for 2025 and 2050, respectively. The yield reduction was related to a rainfall deficit (8.3 – 17.7%) and shortening of the wheat growth period (8 – 36 d). Cultivated land used for rainfed wheat production under the climate change scenarios may be reduced by 15 – 40%. Potential improvements in wheat adaptation for climate change in Iran may include breeding new cultivars and changing agronomic practices like sowing dates.

Keywords: *Temperature, rainfall deficit, simulation, WOSFOST, UKMO*

Introduction

The impact of climate change in many parts of the world has been explored for different crops (Rosenzweig & Parry 1994; Antle 1996; Keating et al. 2001; Attri & Rathore 2003). It has been suggested that some effects of climate change are likely to be beneficial in some agricultural regions (Intergovernmental Panel on Climate Changes [IPCC] 2001). The impact of climate change on agricultural production is related to three major specific factors: Atmospheric carbon dioxide concentration, precipitation and temperature (Holden et al. 2003). There are two counteractive effects from increasing atmospheric CO_2 concentration

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and climate change. Atmospheric CO_2 concentration increase will have positive effects on crop production especially for C3 plants through stimulation of photosynthesis and improvement of water use efficiency (Luo et al. 2003). However, under-water deficit (Kimball et al. 1995) and higher temperatures will usually shorten the growth cycle of a given cultivar (Sayre et al. 1997), and together with reduced water supply are likely to reduce crop production (Turner 2001).

Considerable controversy exists in the literature over changes in yield due to climate change and its magnitude as associated with different scenarios and locations (Aggraval 1994). Results of studies in Canada indicate that future climate change will increase the length of growing season there, making the introduction of late maturing cereal varieties possible and increasing yield (Downing et al. 1997; Boogard et al. 1998). Similar results have been reported in Northern Europe and Australia (Rosenzweig & Parry 1994; Luo et al. 2003). Yield increases of up to 30% have been reported for Australia (Asseng et al. 2004).

Wheat (*Triticum aestivum* L.), a C3 plant species, should benefit from elevated CO_2. However, results of simulation models based on climate change scenarios and the General Circulating Model (GCM) indicate a reduction in the length of the growing season and maturity date in the arid and semi-arid areas of the world (Downing et al. 1997; Turner 2001; Luo et al. 2003), which could cause wheat yield to decline (Menzel & Fabian 1999; Whetton 2001).

A number of climate change impact studies on wheat production around the world have reported varying results. Yield increased under climate change scenarios in Australia, in most cases. Yield gain moderated with increased CO_2 concentration at a higher temperature, and in some cases decreased under a reduced rainfall scenario (Luo et al. 2003). Asseng et al. (2004) found in the Mediterranean environment of Western Australia that the impact of elevated CO_2 and temperature on wheat yield varied with seasonal rainfall amount and distribution. Kosmas and Danalatos (1994) projected that in Greece by 2050 rainfed wheat biomass could decrease by 90, 72, and 53% with rainfall reduction of 65, 50, and 30%, respectively. Attri and Rathore (2003) observed in India an increase of 1.0°C and a doubling of the atmospheric CO_2 concentration could increase wheat yields by 29–37%. However, Attri and Rathore (2003) found further increases in temperature beyond 3°C would negate the beneficial impacts of enhanced $CO_{2,}$ and wheat yield would decrease by 20%.

The climate of Iran is Mediterranean with long dry summers and winter rainfall. The semi-arid Mediterranean environment of Iran is very sensitive to drought and vulnerable to potential future climate changes. Rosenzweig and Parry (1994) predicted that the plant growth period in Iran would decrease significantly and cereal production would decrease by 5–40% under rainfed agriculture by 2080. Bolle (2003) states that even if rainfall does not change, increased risks of drought will result from greater atmospheric evaporative demand in a warmer future climate, soils will dry out faster and prolonged summer droughts might become more frequent and adversely affect wheat yield.

Wheat is one of the main cereal crops of Iran, accounting for 35% of the food grain production of the country (12 million tonnes in 2004). Rainfed wheat accounts for about 60–65% of the land area under wheat production in Iran and contributes 30–35% of wheat production in the country. The demand for wheat is predicted to be over 20 million tonnes in 2025 (Sharifi 2001).

It is important to simulate the growth and yield of wheat under various stress conditions like high air temperature and water deficit to prepare response strategies to future climate change. Most studies have been made under elevated atmospheric CO_2 concentration (Keating et al. 2001) or with increased temperature or water stress (Jamieson et al. 1998). However, few studies have evaluated climate change with concurrent water limitations and rising air temperature. Water limitations and rising air temperatures are important components of future climate change scenarios for countries with dry climates. Water is known to be the most limiting factor for rainfed crop production in these climates and yield has been associated with the amount of water transpired (Monteith 1981).

The purpose of this study is to project the impact of climate change on rainfed wheat production in Iran by the years 2025 and 2050.

Materials and methods

Study site description

This study concentrated on the main rainfed areas of wheat production in west and north-west parts of Iran (Figure 1). Weather data from the nearest weather stations to the main rainfed growing areas from (1968 – 2000) were collected for maximum and minimum temperature, monthly precipitation, monthly and annual potential evapotranspiration and number of sunlight hours. The period 1961 – 1990 is designated by the IPCC (2001) as the baseline against which climate change is to be measured. Weather data for the base-line period (1961 – 1990) for all locations were not available and data for 1968 – 2000 were used instead.

Figure 1. Locations and percentage of rainfed wheat production areas in Iran.

Twelve sites were selected for developing rainfed wheat growth simulations. The range of rainfall in these areas is between 300 and 500 mm/yr. Rainfed areas in Iran have a Mediterranean-type environment with little summer rainfall. Most rainfed wheat production sites are located on soils with low fertility that are shallow and liable to wind and water erosion (Koocheki et al. 2003). In other words, the environment for rainfed wheat production in Iran is vulnerable and climate change may exacerbate this vulnerability.

Climate change scenarios

Climate change scenarios were based on a GCM approach and included the United Kingdom Meteorological Office (UKMO) model. The UKMO climate change scenario for the year 2060 has a resolution (latitude $\times$ longitude) of (5.0×7.5) and CO_2 concentration of 640 ppm, with an average global temperature rise and precipitation increase of 5.2°C and 15%, respectively (Phillips 1994). The adopted UKMO climate change scenarios in this study for years 2025 and 2050 are based on recently published data for the country (Koocheki et al. 2003). Concentrations of CO_2 for these targeted years have been reported to be 425 and 500 ppm (IPCC 2001). The sensitivity of the climatic system to an increase in air temperature, due to greenhouse gas concentrations, was defined as medium (2.5°C) for 2025 and high (4.5°C) for 2050 according to the IPCC (2001). The temperatures enhancement of 2.0 – 3.8°C for winter and summer of 2025 and 2.4 – 4.7°C for spring and summer of 2050 was projected for this experiment. Other climatological models have predicted temperature increase of 2 – 6°C over the next 50 years (Canadian Institute for Climate Studies 2001; Bélanger et al. 2002).

To generate daily weather change scenarios to satisfy the temporal resolution of the crop models, the weather generator model (WEGE) of Richardson (1981) was used. Monthly data for maximum and minimum temperature and precipitation were calculated and converted to the daily values by runs of UKMO that captured 80% of the possible range of climate change. Daily radiation was estimated by the Goudriaan (1993) method. To estimate the radiation intercepted by the crop, atmospheric transitivity of 0.7 was assumed for the present condition and future climate change (Goudriaan 1993).

Simulation of wheat growth and yield

Simulation is one of the main methods of studying potential impacts of climate change on ecosystems (Luo et al. 2003). In this research the World Food Study (WOFOST, v 7.1) crop growth simulation model was used (Van Diepen et al. 1989; Supit et al. 1994). WOFOST is a dynamic, mechanism model validated in a wide variety of environments.

The WOFOST model

The WOFOST model was employed in this study using long-term weather data (1968 – 2000). This model was developed in The Netherlands to stimulate climatic conditions, soil properties and water balances. The main components of the plant growth model are phenological development, assimilation, respiration and evapotranspiration. Calculations of potential evapotranspiration are based on the methods of Monteith (1981), while actual transpiration rates are calculated from maximum transpiration rates. The reduction factor for transpiration is defined as Potential Evapotranspiration divided by Actual Evapotranspiration (PET/AET). The highest possible value of PET/AET is set at 1, which means no water stress and the lowest possible value is set at 0.

The method of Eitzinger et al. (2000) was employed to calibrate and evaluate the model, and their coefficients were used in the model for the Sadari cultivar (Tao 1993). Sardari is the major rainfed winter wheat cultivar in Iran. Model performance was tested by using the root mean square error (RMSE) as indicated below:

$$\mathrm{RMSE} = \left([\mathrm{Y}^{\mathrm{sim.}} - \mathrm{Y}^{\mathrm{obs.}}]^2/n\right)^{-1/2}$$

$\mathrm{Y}^{\mathrm{sim.}}$ and $\mathrm{Y}^{\mathrm{obs.}}$ are simulated and observed (measured) wheat yield values and n is the number of observations.

Results and discussion

The WOFOST model predicted the growth and development stages of the Sardari variety in different locations reasonably well. The WOFOST growth simulator was first run for different locations with data collected from GCM in 2025 and 2050 according to temperature rise scenarios. The uncertainities in rainfall were assumed to be between -15 to $+20\%$ of the normal rainfall for the respective locations.

Simulated vs. measured wheat yield is shown in Figure 2. Simulated yields were in the range of $0.51-0.97$ t ha^{-1} and measured yields ranged from $0.54-0.92$ t ha^{-1} with the mean and standard deviation (SD) of 0.70 (0.19) and 0.67 (0.17) t ha^{-1}, respectively. Simulations were performed in Mashhad in the north-east part of the country in 1998 and 2002. The WOFOST model provided good estimations of wheat yield with RMSE of 0.047 t ha^{-1}, which is about 7% of the mean observed wheat yield. However, in years with severe drought, the difference between observed and simulated yield were much higher. There is a possibility that the WOFOST model may not be able to simulate growth under severe conditions (Aggraval 1994).

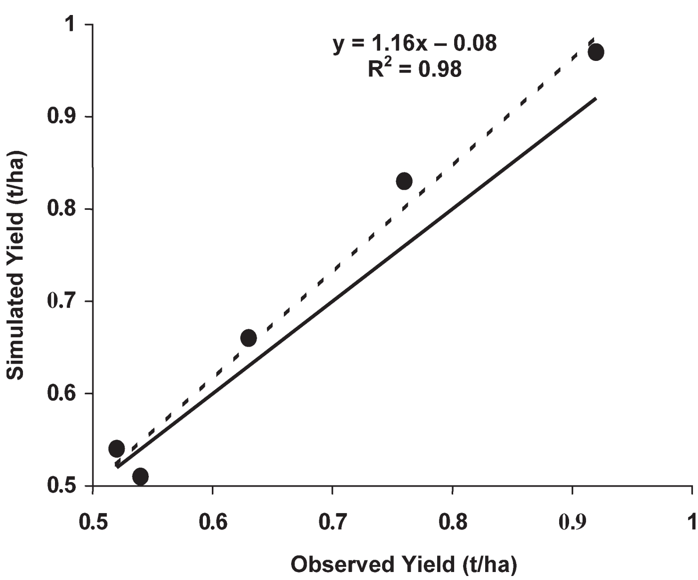

Figure 2. Comparison of simulated vs. observed grain yield for Sardari wheat cultivar. The solid line is 1:1 line and broken line is the regression.

Rainfed wheat yield and growth rate under climate change

Data in Table I show a persistent growth rate reduction on the order of 21–41% and yield reduction on the order of 15–33% in different locations for years 2025 and 2050, respectively. Average yield and growth rate reduction was 20 and 27 for 2025 and 26 and 36 for 2050. The UKMO model scenario predicted similar results for wheat production in Egypt where wheat yield changed between −25 to −51% with a 5.2°C increase in air temperature in 2060.

Growth and yield reduction results in Table I are in agreement with Attri and Rathore (2003), Rai et al. (2004) and IPCC (2001) findings that temperature increase in the order of 3°C or higher can have adverse effects on wheat grain yield. In this experiment, the rise in air temperature during the growth period (spring and summer) for the Sardari cultivar was predicted to be 3.5 and 4.3°C for 2025 and 2050, respectively.

Elevated temperature is also known to enhance the growth rate of crops (Turner 2001). However, growth rate or yield is also directly influenced by moisture deficiency (Hammer & Muchow 1991). Data in Figure 3 show the evapotranspiration and growth rate of the Sardari wheat cultivar in Kermanshah under the predicted climate change scenario in the year 2050. Kermanshah is one of the major rainfed wheat production areas in Iran (Figure 1). Data in Table I provides estimates that under the predicted climate change scenario in the year 2050, yield and growth rate of the Sardari cultivar will be reduce by 27 and 36%, respectively.

Wheat growth rate presented in Figure 3 is the product of the amount of radiation absorbed (J/m^2/day) and the radiation use efficiency (gDM/J energy) (Monteith 1981). Effect of climate change on incoming radiation in Iran has been reported to be negligible (Koocheki et al. 2003), however, the plant receptive surface for radiation sorption or leaf area index (LAI) is known to vary according to moisture availability. Keating et al. (2001) suggested that LAI begins to decline when water availability in soil is reduced to 45%. Sharifi (2001) reported moisture deficiency was responsible for lower LAI in many rainfed wheat growing areas in Iran.

Table I. Percentage of mean growth rate and yield reduction in different locations for years 2025 and 2050 compared to year 2000.

	Growth rate reduction (%)		Yield reduction (%)	
Location	2025	2050	2025	2050
Arak	21	34	18	24
Hamedan	28	37	22	29
Kermanshah	27	36	20	27
Khorram Abad	29	37	22	28
Khoy	24	35	20	31
Orumyeh	28	39	16	23
Qazvin	29	38	25	33
Saghez	24	33	19	26
Sanandaj	21	32	17	25
Shahr e Kord	30	41	21	29
Tabriz	23	36	15	21
Zanjan	23	38	24	31
Average	26	36	20	27

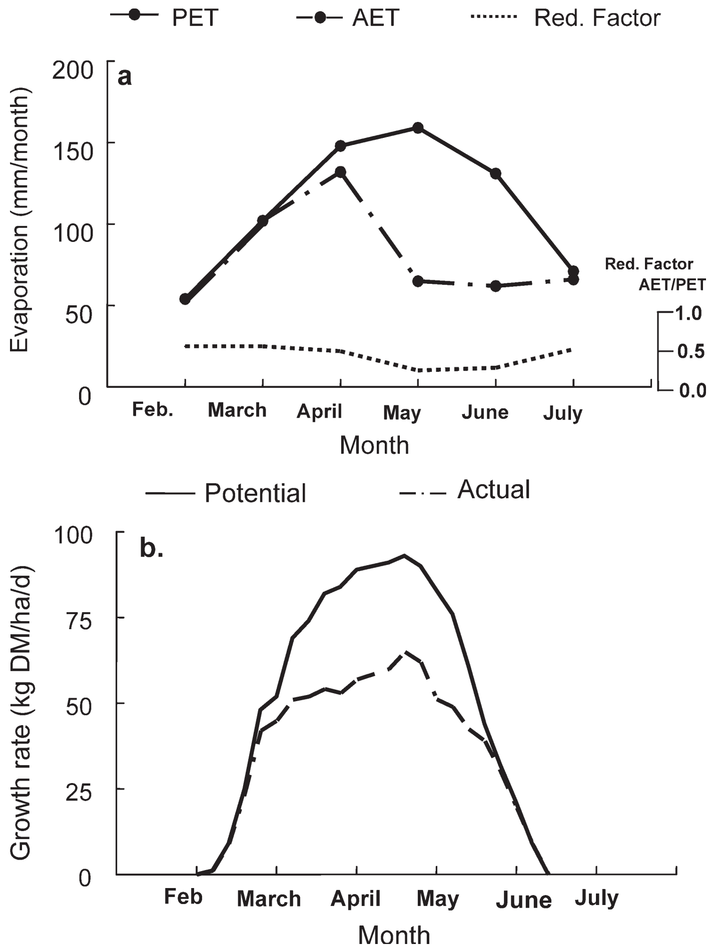

Figure 3. Evapotranspiration and growth rate of Sardari wheat cultivar in Keramansha under the predicted climate change scenario in the year 2050.

Growth rate is generally evaluated by the ratio of actual evapotranspiration to potential evapotranspiration (AET/PET) (Figure 3a). This ratio is called the growth rate reduction factor and is equal to unity when there is no water deficiency during the growth period. However, at the height of the growth period in these rainfed areas, the growth rate factor (AET/PET) is normally less than 1 (Figure 3a), which indicates moisture deficiency and usually translates to lower growth rate (Figure 3b). To calculate reduction in growth rate, the reduction factor has been multiplied by the potential growth rate (Goudriaan 1993) (Figure 3b). The Close relationship between the growth and transpiration rates of the Sardari cultivar grown in Kermanshah during the growth period from March to June can be applied to other rainfed wheat production areas in the country (Figure 3a and 3b), as predicted by UKMO model. The UKMO model has predicted yield reduction and decreases in water availability for other locations (Tubiello et al. 1999; Yates & Strzepek 1998). However, Holden et al. (2003) cautioned that precipitation scenarios are inherently less reliable than temperature given the inherent uncertainities of GCMs with respect to this spatially variable feature of climate.

Potential of rainfed wheat production under climate change

Rainfed wheat production largely depends on stored soil moisture. Increased air temperature combined with decreasing rainfall affects evapotranspiration and can significantly reduce the water available for plant growth (Figure 3). Increased temperature also leads to rapid accumulation of growing degree days and faster development, growth and maturity of wheat (see Table II). Under sufficient water supply, air temperature rise may provide longer potential growth days but under deficient water supply, as in rainfed cultivation in arid and sem-iarid climates, high air temperature translates to shorter growth periods. For example, in Khoy (Table II, Figure 1), a major rainfed wheat production area in Iran, time of water deficit could increase by 21 d and growth period could decrease by 37 d in year 2050 with respect to year 2000. Potential growth period was calculated by integration of temperature above zero and moisture availability (Koocheki et al. 2001). Abrol et al. (1991) reported that a 1°C temperature enhancement in India resulted in a 9-d reduction to maturity. Similarly, Rai et al. (2004) reported that an increase in temperature between 1 and 3°C could advance the optimal sowing dates by 5–8 d for each degree rise in temperature and a shorter potential growth period.

Average potential growth days in Table II are predicted to decrease by 15–30 d and days with water deficit to increase by 9–18 d in years 2025 and 2050, respectively. These changes will affect the date of Sardari wheat harvest. Harvest date is expected to be 3–5 weeks earlier in 2050 due to moisture deficiency or rainfall deficit (Table II) (Rai et al. 2004). Turner (2001) and Menzel and Fabian (1999) suggested that wheat grain maturity date and yield reduction could be caused mainly by extended moisture deficient periods during climate change.

Data in Figure 4 show rainfall deficit and estimate yield reduction probability based on the Monteith (1981) approach for four major wheat production regions in 2050. Rainfall deficit index was constructed by subtracting daily PET from daily rainfall (Table II). Yield reduction for these areas follows a normal distribution with future predicted climate change (Figure 4). The highest probability of yield reduction is between 15 and 30% regardless of location. The average yield reduction for these locations was predicted to be about 24% with rainfall deficit

Table II. Number of potential growth days (days without freezing) and number of dry days with water deficit (days with water deficit) for years 2025 and 2050 compared to year 2000.

	Potential growth days			Days with water deficit			Rainfall deficit index, mm		
Location	2000	2025	2050	2000	2025	2050	2000	2025	2050
Arak	219	204	192	176	184	192	68	80	95
Hamedan	181	170	162	165	174	184	76	88	103
Kermanshah	208	189	173	177	185	194	77	89	100
Khorram Abad	258	222	203	203	213	222	72	90	99
Khoy	215	201	178	176	188	197	69	77	90
Orumyeh	217	201	183	170	180	189	72	84	98
Qazvin	217	200	182	167	174	184	83	100	116
Saghez	184	173	161	220	229	236	71	85	97
Sanandaj	204	188	172	164	173	182	81	93	105
Shahr e Kord	183	171	160	207	215	223	65	80	93
Tabriz	221	208	190	156	163	173	70	87	94
Zanjan	184	176	165	169	181	190	74	88	101
Average	207	192	177	179	188	197	73	87	99

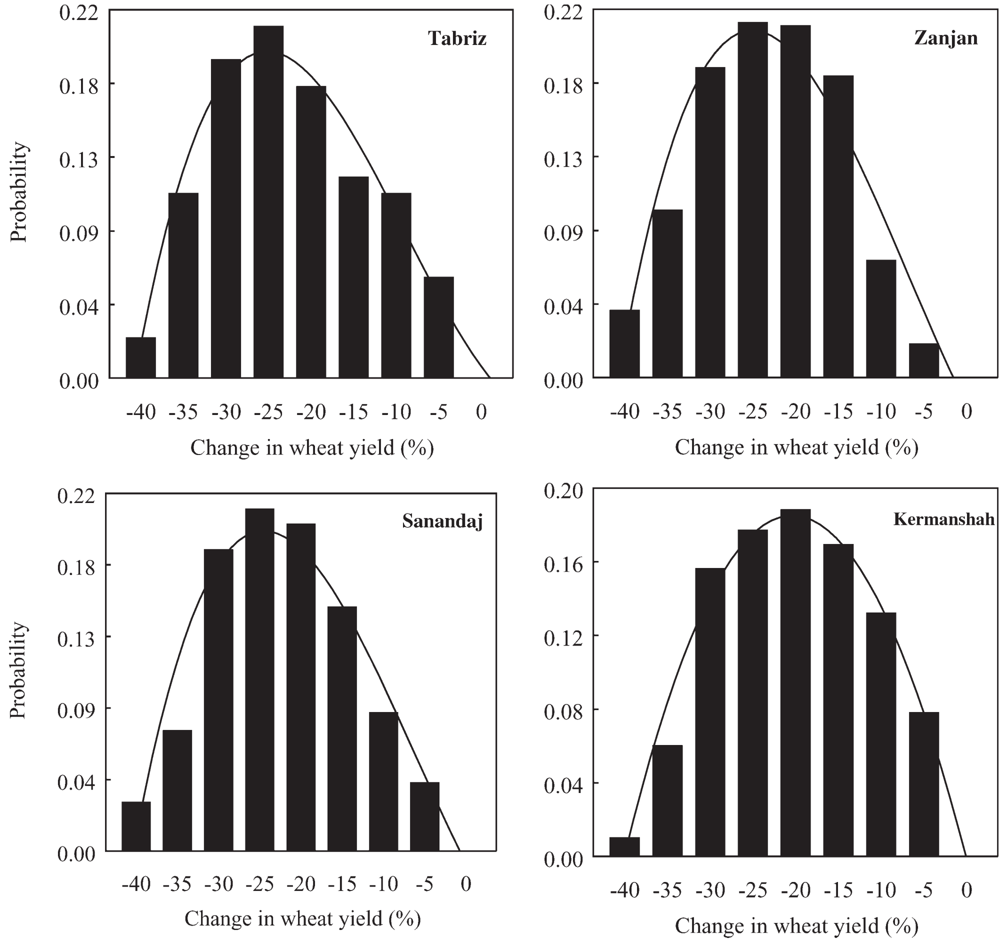

Figure 4. Yield reduction probability in 4 major rainfed wheat production areas from future climate change in 2050.

increase by 26.1 mm in 2025 or 35% in 2050. Similar yield reduction and decrease in rainfall deficit of the order of 25% to over 40% has been suggested for the rainfed wheat production in some parts of the US in scenarios generated for 2050 and 2080 (Rosenzweig & Parry 1994).

Under increased rainfall deficit, there is also the possibility for cultivated rainfed wheat lands to diminish, be abandoned, or become available for other practices. There are studies that show water deficit increasing and local climate change land productivity diminishing to the point that land will be abandoned (Tao 1993; Hoogenboom 2000; Howden & Jones 2001). Van Diepen et al. (1989) has suggested that farmers may be able to tolerate some yield reduction if it is less than 10%. However, when yield reduction under climate change is more than 10%, cultivated areas may reduce in proportion to yield reduction (Howden & Jones 2001).

Figure 5 was constructed from information obtained in Table I and Figure 4 and shows changes in the percentage of cultivated rainfed wheat production areas in relation to yield reductions under three different scenarios in 2050. Scenarios are: cultivated land will be reduced in a 1:1 ratio with respect to yield reduction, or arable land will be reduced in an

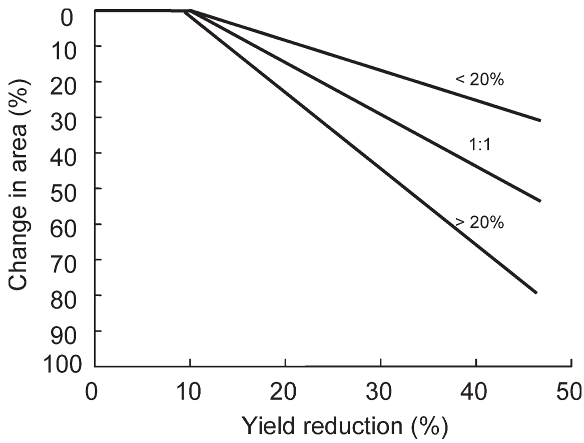

Figure 5. Changes in the percentage of cultivated rainfed wheat production areas in relation to yield reductions under three different scenarios of land reduction to cultivated land change in 2050.

amount equal to 20% above or below the level of 1:1 yield reduction to land change. This simple method shows that with a 30% reduction in yield, between 15 and 40% of cultivable rainfed land may be removed from wheat production. Under a 1:1 yield to land reduction ratio, the reduction of rainfed wheat cultivation is projected to be in the range of 16–25% in 2025 and 23–33% in 2050. Such decreases, if realized, would clearly have profound implications for rainfed wheat production in Iran.

Conclusions

Under the climate change scenarios used in this study, all rainfed wheat growing areas in Iran will likely experience substantial modification in agroclimatic indices that will affect their productivity. Agroclimatic indices were predicted to be warmer conditions with less precipitation. Warmer temperature and less precipitation would reduce growth period duration, increase days with water deficit and reduce cultivated land used for rainfed wheat production.

National mean yield predicted for the base-line climate (1968–2000) was 900 kg ha^{-1} ranging from 500 kg to 3.5 t ha^{-1}. The geographical distribution of yield potential was not predicted to change in 2025 and 2050 but the yield in all areas was predicted to decrease, with possibly greater decreases to the east. Yield was reduced for all studied sites by about 18% in 2025 to 25% in 2050. Potential improvements in wheat adaptation for climate change in Iran may include breeding new cultivars and changing agronomic practices like sowing dates.

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